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Original article

Geometric decomposition and algorithmic model of main gate muqarnas of Ankara Cenabi Ahmet Pasha Mosque

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ABSTRACT

Cenabi Ahmet Pasha Mosque (Cenab-ı Ahmet Paşa Mosque) is known to be the only work that resembles the style of Architect Sinan in Ankara. In this study, it is aimed to examine the two-dimensional muqarnas scheme of the mosque's main gate and to determine through algorithmic modeling the combination of muqarnas cells in the third dimension. By the photogrammetry method, the grid and star forms used in the muqarnas plan scheme are revealed. The geometric characteristic of the muqarnas in two dimensions is determined. Cell types of the muqarnas and their geometric configurations are obtained. It is demonstrated that there is a radial grid in the plan of the Cenabi Ahmet Pasha Mosque main gate muqarnas, and that the three-dimensional structure of the muqarnas consisting of six layers includes almond cell, triangle cell, deltoid cell, intermediate triangle cell, intermediate deltoid cell, biped cell and triped cell. Additionally, an algorithmic model based on the creation of cell unit system is proposed for the creation of the muqarnas geometry in 3D.

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1. Introduction

Muqarnas can be defined as a three-dimensional ornamental element used in Islamic architecture. This element can be found in various building parts of a building such as main gates, column heads, mihrabs, lower parts of minaret balconies, and dome transition elements. Although this architectural ornamental element appears to have a complex pattern when viewed from the outside, it is actually shaped by various three dimensional geometrical cells. The plate found at Takht-i Sulayman represents the earliest known muqarnas projection plan [1,2]. Various muqarnas drawing schemes can be found in the Topkapi Scroll [2], Takahashi's [3] and Uluengin's [4] drawings. It is understood from the muqarnas drawings in the Topkapı Scroll that a two-dimensional layout was prepared before the muqarnas were built. The star patterns, which are also seen in the ornaments called Islamic geometric patterns [5,6], can be found on these layouts. In addition, it is also seen in the drawings on the Topkapı Scroll [2] that there are auxiliary/reference lines on these layouts. These reference lines can be straight lines or circles. The star patterns, which consist of different number of arms, usually fill the reference circles.

Muqarnas geometries can be analyzed in 2D and 3D in order to understand their structures and compare compositions. As it is explained in the Background section, while many muqarnas schema analyses have been carried out, many muqarnas schemas yet remain unstudied. Also, most of the studies focus on the 2D muqarnas plan studies while 3D studies are very limited.

1.1. Research aim

This study aims to examine the two-dimensional muqarnas scheme of the main gate of Cenabi Ahmet Pasha Mosque according to the theory of shape grammar, and to determine the combination of muqarnas cells in the third dimension. Also, an algorithm based on the creation of cell unit system has been proposed for the creation of Cenabi Ahmet Pasha Mosque main gate muqarnas prototype.

1.2. Background

According to the inscription tablet that can be found in the facade of the mosque, it is known that Cenabi Ahmet Pasha Mosque in Ankara was built by Cenabi Ahmet Pasha between 1565 and 1566 during the reign of Suleiman the Magnificent [7]. It is one of several single-domed mosques with squinches (trompe) built during the period of Architect Sinan, possesing an entrance *revak* with three openings [8]. Cenabi Ahmet Pasha Tomb (*Türbe*) and Azımı (Hacı Esat Efendi) Tomb (*Türbe*) are located in Cenabi Ahmet Pasha Mosque's courtyard. This mosque, located on Ulucanlar Avenue in the Altındağ district of Ankara, is also known as the Yeni Mosque.

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Fig. 1. Main façade of Cenabi Ahmet Pasha Mosque and the result of the 3D scanning of main gate muqarnas.

As Karademir [9] mentioned in his thesis, Ülgen [10] and Öney [11] suggested that this mosque may not have been designed by Architect Sinan, but by his students. It is known that the building has undergone many renovations [12,13]. However, the main gate muqarnas of the Cenabi Ahmet Pasha Mosque seem to have preserved their originality to a large extent. Yet, Karademir [9] stated that the ornamental tassels on the main gate muqarnas were renovated pointed out that the bulb-shaped part at the end of these ornamental tassels did not provide integrity with the body, indicated that they may have been added later. Since main gates of buildings [14,15] are decorated with the most elaborated muqarnas, this study focuses on main gate muqarnas of Cenabi Ahmet Pasha Mosque. In addition to main gate muqarnas, there are four smaller ones in the main facade and one in the interior of octagonal shape in this mosque.

Many muqarnas look different from each other. Based on the study of plans of many muqarnas, Uluengin [4] concluded that different muqarnas schemes were based on different regions of a larger scheme. For example, for muqarnas under the minaret balcony, a section in the scheme can be used as a layout by determining its borders as a circle [4]. Although muqarnas can be associated with different parts of the schemes, muqarnas are still very diverse in their plans and third-dimensional cell arrangements. Muqarnas consist of cells in the third dimension. These cells are named according to their geometrical form types [16].

Existing scholar work addresses two questions: Studies of existing muqarnas and creation of muqarnas typologies. Works of Özdural [17], Notkin [18], Tabbaa [19], Büyükdiğan [20], Yaghan [21], Kashef [22], Gonzalo and Alkadi [23], Gámiz-Gordo and Ferrer-Pérez-Blanco [24], Ferrer-Pérez-Blanco et al. [25], Güzelci et al. [26], Dinçer and Duru [27], Dinçer [28], Agirbas et al. [29] and Gámiz-Gordo et al. [30] examine existing muqarnas. Algorithmic 3D creation of muqarnas was studied by the following authors. Harmsen [31], focused on the muqarnas geometry of the Seljuk and Il-Khanid periods. Hamekasi et al. [32] created algorithmically muqarnas on the base of 2D information of each muqarnas layer connecting the layers through B-spline curves and surfaces. Gherardini and Leali [33] proposed the inclusion of the photogrammetry method in addition to the usage of 2D plan drawings to reconstruct muqarnas geometry in 3D. Senhaji and Benslimane [34] proposed an algorithm to create 3D muqarnas geometry from 2D plan of muqarnas, by matching a 2D cell plan and its neighboring properties with possible 3D cell units of Moroccan-Andalusian style muqarnas. Senhaji and Benslimane [35] proposed an algorithm with the same logic, but for the construction of circular muqarnas elements. Agirbas and Yildiz [16] proposed a 3D parametric muqarnas creation model based on the individual cell unit algorithmic modeling. Alaçam et al. [36] proposed a model for creation of 3D muqarnas with the use of folding principle. Dinçer and Yazar [37] compared 3D muqarnas digital reconstruction methods; namely element-based, tessellation-based and block-based workflows. Variety in the muqarnas geometry requires development of a variety of algorithms and methods.

2. Material and method

According to on-site measurements, the length of the main gate of Cenabi Ahmet Pasha Mosque muqarnas is 210 cm and its width is 105 cm (plan projection dimensions). The stone material was used in the construction of the muqarnas. The muqarnas section of the main gate was photographed. From 250 photographs the photogrammetric 3D model was created in the Polycam software (Fig. 1). The plan of the muqarnas was made from the orthophoto obtained with the help of 3D photogrammetric model (Fig. 2). AutoCAD is used to trace the 2D plan as well as to work out the geometric decomposition of the plan and its sequence. Next the steps of muqarnas plan creation were formulated within the framework of the shape grammar theory. According to the shape grammar theory [38,39], new shapes are formed on the basis of rules. For example, if a square is duplicated (application of duplication as a rule), a rectangle (a new shape) is formed. As mentioned by Ostwald and Lee [40], the shape grammar methodology is used for identifying the formal properties of various designs. The plan of muqarnas was used to build an algorithmic model in the Grasshopper. Finally, the coding of the algorithm produced the 3D model of muqarnas. The details about the coding process are explained in the Results section.

In this study, parametric coding of individual solid muqarnas cells in the proposed algorithmic model was made through the extracted points from the plan. Afterwards, the cells were copied or mirrored to the relevant parts in line with the plan. The muqarnas cell types in Cenabi Ahmet Pasha Mosque main gate muqarnas are similar to the muqarnas cell types in many buildings built by Architect Sinan. Therefore, using the 2D plan, an algorithm can be written that can automatically assigns parametrically modeled cell types to the relevant parts. The 3D cell type can be clearly

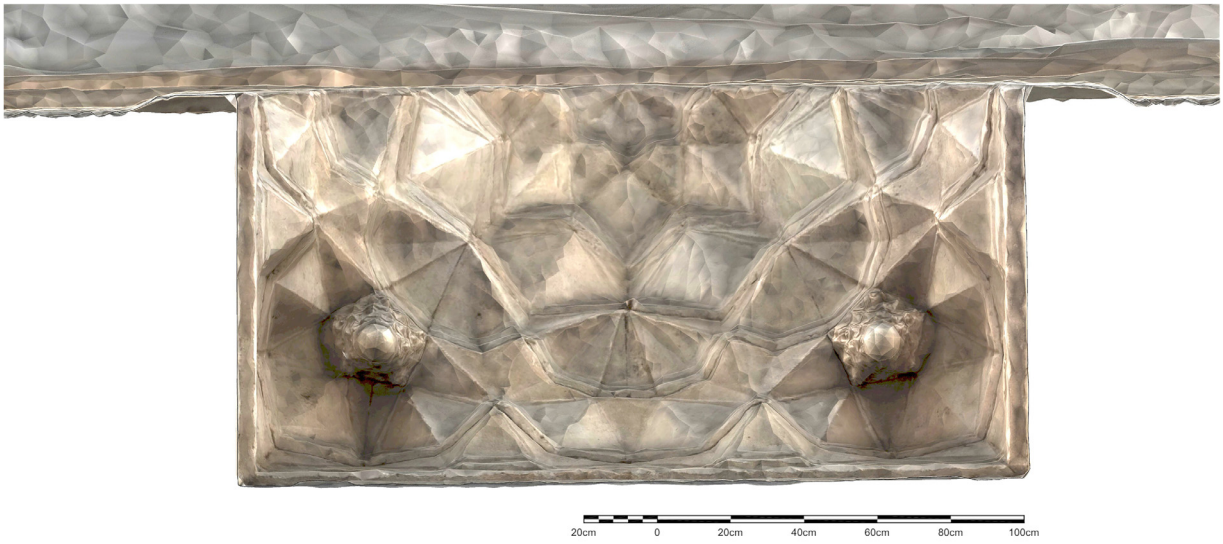

Fig. 2. The plan of the Cenabi Ahmet Pasha Mosque main gate muqarnas obtained from the 3D scanned data.

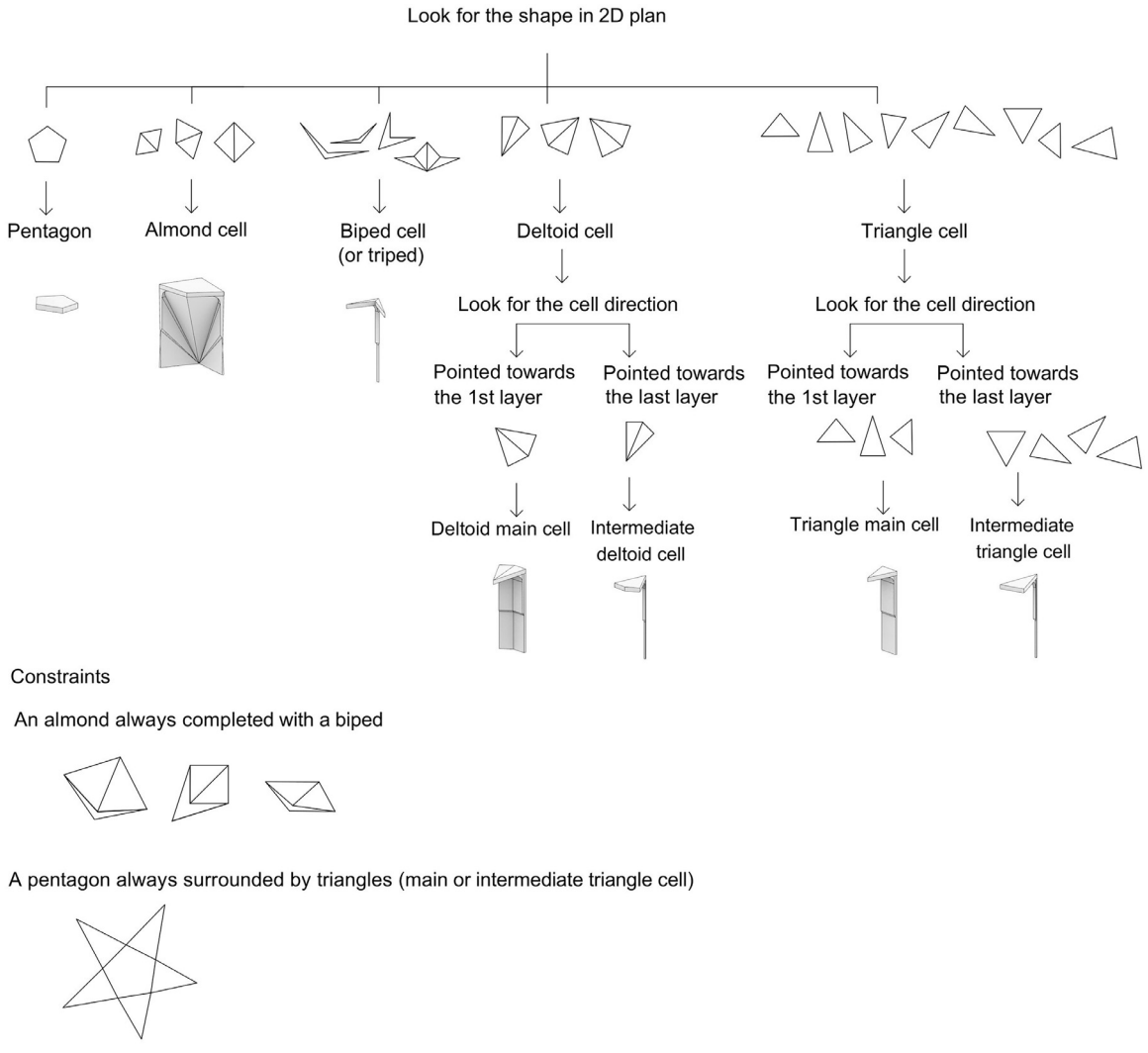

Fig. 3. Workflow of the potential automated algorithm.

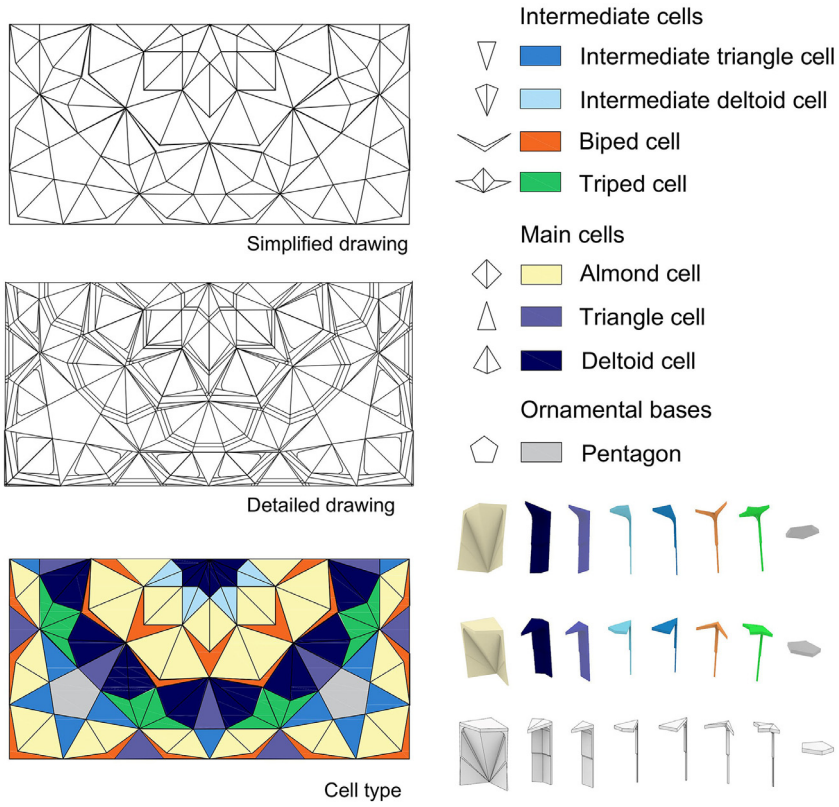

Fig. 4. The Cenabi Ahmet Pasha Mosque main gate muqarnas plan and its cell types.

determined from the 2D plan drawing. For example, the almond shape in 2D plan corresponds to an almond cell in 3D (Fig. 3). There is no other possible option. Likewise, the biped shape in the 2D plan corresponds to a biped cell in 3D. The triped cell is formed by the combination of two biped cells. However, the sizes of almond and biped cells can vary greatly, even in the same plan. The repetitive shapes are more commonly used in the muqarnas plans of the Seljuk period than in the plans of the Ottoman period. The type of cell can have many different sizes in different tiers. Therefore, in many plans, a repetitive scheme is not encountered in contrast to the Seljuk period muqarnas plans. However, symmetry always exists in every muqarnas plan. In the case of creating an automated algorithmic model, creating parametric individual cells helps to easily modify the size of the cells. The 3D cell corresponding to the deltoid shape in the 2D plan can be one of the two types: deltoid intermediate cell or deltoid main cell. In this case, the choice should depend on the direction of the deltoid in the 2D plan. If the pointed tip of the deltoid drawing in the 2D plan is towards the starting star (half star in the first layer), the deltoid corresponds to the deltoid main cell in 3D. However, if the pointed tip of the deltoid drawing is in the opposite direction to the starting star, the deltoid corresponds to the deltoid intermediate cell in 3D (Fig. 3). The same applies to the triangular shape in the 2D plan. The 3D cell corresponding to the triangular shape in the 2D plan can be one of the two types: triangle intermediate cell or triangle main cell. In this case, the choice should depend on the direction of the triangle in the 2D plan. If the pointed tip of the triangle drawing in the 2D plan is towards the starting star (half star in the first layer), the triangle corresponds to the triangle main cell in 3D. However, if the pointed tip of the triangle drawing is in the opposite direction to the starting star, the triangle corresponds to the triangle intermediate cell in 3D. In the case of creation of an automated algorithm using a 2D plan, such a mechanism can be used (Fig. 3). However, layer information must be given to the algorithm manually, due to the absence of information of the layers in the 2D plan. Furthermore, in the case of creating an automated algorithm, various constraints can also be included in the mechanism. For example, in muqarnas plans, an almond cell is always completed by a biped cell [41]. Also, a pentagon is always surrounded by triangle cells (main or intermediate triangle cell). These situations can be considered as constraints (Fig. 3). The suggestion of this automated algorithm was derived as a result of studies on the geometric infrastructure of muqarnas. However, its development is not within the scope of this study and remains to be researched in future studies.

3. Results

Fig. 4 reveals that the muqarnas composition contains many different cell types, shown in different colors. Terminology for cell types varies in the literature [4,31]. The term ‘almond’, which represents one of the commonly used cell type in the muqarnas, was adopted from Uluengin’s [4] study. Other cells were named according to their geometric features. Some of the cells can be named as main cells which have bigger bodies than the other cells. Examples of this type are almond cell, triangle cell and deltoid cell. Some of the cells can be named as intermediate cells which have tiny bodies. Examples of this type are intermediate triangle cell, intermediate deltoid cell, biped cell and triped cell. Another cell type is the ornamental base. This part is in the form of a pentagon in the main gate muqarnas of the Cenabi Ahmet Pasha Mosque. On this part, ornamental tassels are placed. It can also be seen that this part forms the center of the star patterns in the muqarnas plan. In the main gate muqarnas composition of the Cenabi Ahmet Pasha Mosque, the stars are five-armed and are located in the lower right and left corners of the muqarnas plan frame. The arms of these stars are unequal. Cells of the same type in the composition can be in different sizes.

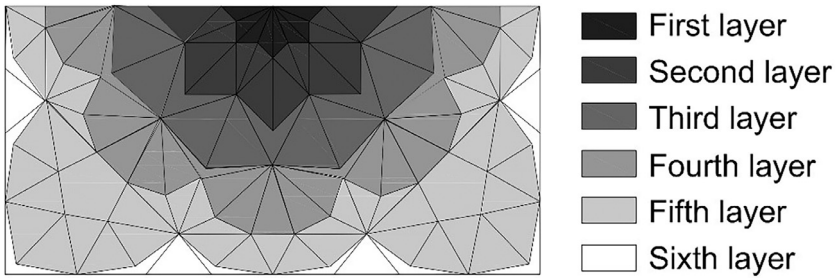

Fig. 5. 3D layers of the Cenabi Ahmet Pasha Mosque main gate muqarnas.

The main gate muqarnas of Cenabi Ahmet Pasha Mosque consists of six layers in the third dimension (Fig. 5). The contents of the layers are as follows: deltoid cells are in the first layer; intermediate deltoid cells and almond cells are in the second layer; biped cells and almond cells are in the third layer; triangle cells, deltoid cells and biped cells are in the fourth layer; intermediate triangle cells, almond cells, triped cells and pentagon are in the fifth layer; triangle cells and biped cells are in the sixth layer. While four arms of the five-armed stars in the muqarnas composition are in the fifth layer, one arm is in the fourth layer. Each arm can be counted as one cell.

The geometric decomposition of the plan of muqarnas at the main gate of Cenabi Ahmet Pasha Mosque is done within the framework of shape grammar theory [38,39] as explained in the Methodology section. This is described with steps below. Fig. 6 shows this geometric decomposition step by step. In the muqarnas plan, new geometries created within the steps are shown in blue color, the reference layout is shown in gray color, and previous geometries are shown in red color.

It is known that circular layouts are used in Anatolian Seljuk architectural ornament constructions. In this study, the geometry of muqarnas is solved in an octagon with sub-stages. The octagon can actually be formed from a circle.

- Step 1: A radial layout is drawn (Fig. 6).
- Step 2: Evenly spaced octagons are placed on the radial layout. However, the proportion of the first octagon to the center is square root of 2. The number of these octagons can be increased or decreased according to the structure of the pattern. The radial layout and the octagonal layout are the reference lines required to create the muqarnas plan (Fig. 6).
- Step 3: The eight-pointed star is placed in the center of the layout. The eight-pointed star is the center of the stars that are intertwined and getting smaller and smaller. This star is composed of deltoid cells (in the first layer in 3D). To form this eight-pointed star, a single deltoid is created. Then the deltoid is copied and rotational symmetry applied to obtain eight deltoids in total in order to form the eight-pointed star. After one eight-pointed star was created in the center of the radial grid, a deltoid has been added to a concave part of the eight-pointed star. Then, the deltoid has been copied with application of rotational symmetry. As a result, eight deltoids (intermediate deltoid cells in the second layer in 3D) have been added to the concave parts of the star around its center (Fig. 6).
- Step 4: A second eight-pointed star is formed around the eight-pointed star. This star is composed of bipeds and almond cells in the third dimension. To form this star, one polygonal shape representing biped is added to the one edge of the eight-pointed star. Then, this shape is copied with application of rotational symmetry to form the second eight-pointed star (Fig. 6).
- Step 5: A third eight-pointed star is formed around the second eight-pointed star. This star is also composed of bipeds and almond cells in the third dimension. To form this star, eight polygonal shapes representing bipeds are also added with application of rotational symmetry to the edges of the second eight-pointed star (Fig. 6).
- Step 6: Deltoid cells are placed around the third eight-armed star. Two deltoid cells are placed on each side of the octagon in the layout. While doing this procedure, first a deltoid cell plan is drawn, and then this cell plan is mirrored. Afterwards, this double deltoid plan is copied around the center of rotational symmetry (Fig. 6).
- Step 7: Eight copies of a triped cell are placed between the double deltoid cells with application of rotational symmetry. One triped cell consists of four triangles (Fig. 6). Through step 4 to 7, the elements are supported-aligned to the series of octagons in step 1.
- Step 8: A rectangular frame based on the boundaries of the whole pattern is added to the pattern. The creation of the five-pointed star starts with the extending lines of first arm (in fourth layer in 3D) to the point where the frame and 9th octagon of the grid intersects. Afterwards, lines between the intersection points and 8th octagon of the grid are drawn. Therefore, three arms of the five-pointed star are formed (Fig. 6).
- Step 9: Remaining two arms of the five-pointed star are formed by connecting intersection point in the 8th octagon of the grid with the vertices of tripeds in the 6th octagon of the grid (Fig. 6).
- Step 10: Four copies of the five-pointed star are placed with application of rotational symmetry. These stars can be seen in Fig. 6 in blue.
- Step 11: The parts outside of this frame, which are added in accordance with the dimensions of the muqarnas plan, are eliminated from the plan drawing. Also in this step, the biped cells used throughout the frame are placed in the muqarnas plan drawing. The polygonal shapes representing biped cell plans are added to the outer parts of the five-pointed stars (Fig. 6).
- Step 12: Triangle drawings have been added to the muqarnas plan. These triangles contain elements of five-pointed stars.
- Step 13: Layout traces are eliminated from the plan. Almond cells are placed in the corresponding gaps by adding lines in accordance to the radial grid (Fig. 6).

To develop the algorithmic model, the muqarnas plan was transferred to Rhino software. The coding was done with the use of half muqarnas plan layout. First, a 2-dimensional diagram of the half plan was created in Grasshopper software with circles divided into segments. The endpoints of the segments were used to create 2D scheme (the grey color part of the script in Fig. 7), that provided the base for the 3D construction. As shown in Fig. 7, the

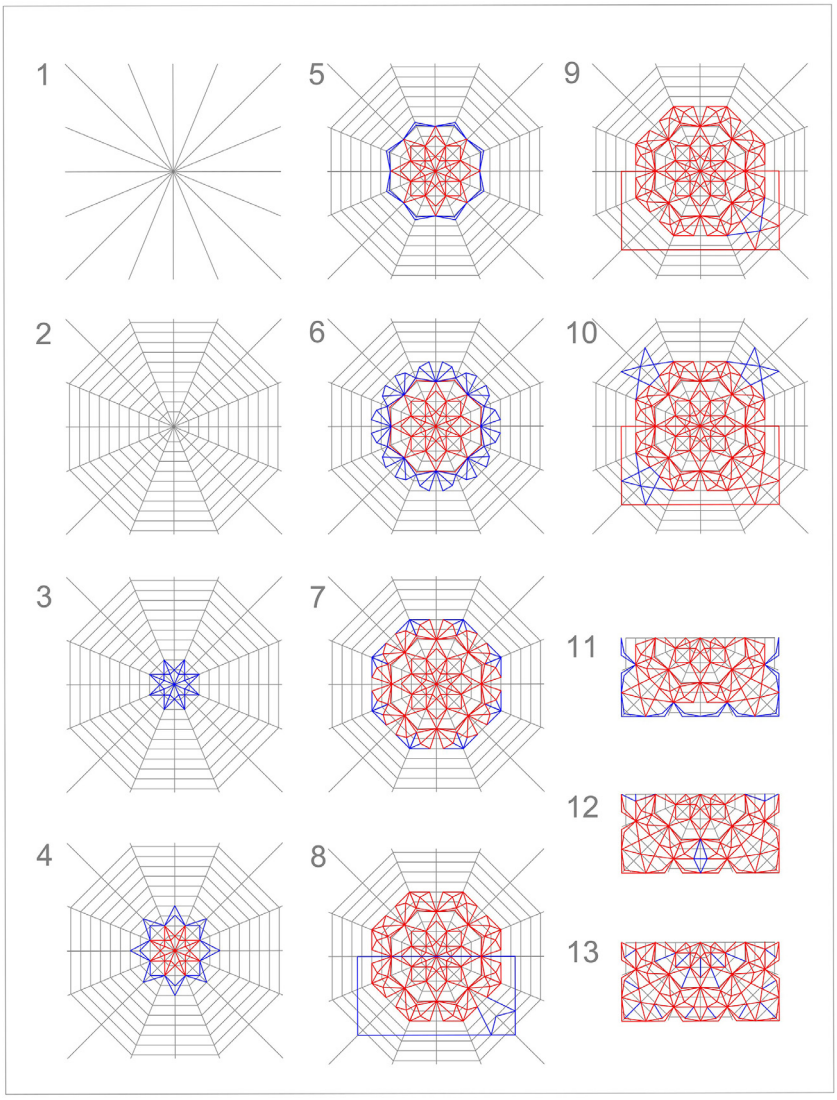

Fig. 6. The steps of creating the plan of muqarnas through the radial layout at the main gate of Cenabi Ahmet Pasha Mosque.

codes for different cell types were grouped separately and represented in different colors. The colors used in Fig. 8 correspond to these code groups. For example, almond cells were colored yellow, biped cells were colored orange and triped cells were colored green. If a layer contains a type of cell with different dimensions, these were grouped separately but assigned the same colors. First, the bottom layer (6th layer) of the muqarnas was taken into consideration and the coding process was started. The cells in the bottom layer were created by moving the points that used to create the lines in the plan, to the Z axis. The cell units were not formed as a single surface, but in the form of a solid object. For the creation of surfaces from the lines, components of Loft, Boundary surfaces and Edge Surface were used. For example, in 6th layer, using this logic, 2 types of biped cells and 1 triangle main cell type were created. For cells of the same type and size in the same layer, mirroring was performed after the relevant symmetry axis was defined in the code. These parts were colored red in the code shown in Fig. 7. After these cells were created, modeling of the next layer was started. The points in the plan were lifted to the relevant layer to create 3D cells. The rest of the layers were also coded using the same logic. Although the layer heights were kept the same in each layer, this measurement can be adjusted as desired since it was defined parametrically. Therefore, the dimensions of the cells can be parametrized in the same way. After each layer was coded with the same logic, the cells were mirrored and the muqarnas was completed. The units were colored in Rhino software to see the geometric composition of the muqarnas in 3D (Fig. 8).

Modeling the existing muqarnas with usual 3D modeling techniques (software that allow form creation without coding) makes it difficult to reshape the muqarnas geometry. On the contrary, it is more efficient to do coding-based modeling in order to make changes in shape and size of the geometry. Thus, the dimensions, indentations and protrusions of the cells can be reshaped parametrically.

4. Discussion

In his book, Fatin Uluengin [4] listed the name of 552 muqarnas drawings that he had drawn (the book does not include all the drawings), but they do not include the muqarnas of Ankara Cenabi Ahmet Pasha Mosque. Takahashi's [3] had drawn Cenabi Ahmet Pasha Mosque main gate muqarnas plan. The scheme of the Cenabi Ahmet Pasha Mosque main gate muqarnas plan, which we have drawn with the information obtained from 3D photogrammetric model in this study differs from Takahashi's [3] plan mainly in terms of biped cells. Biped cells, which affects the cell propor-

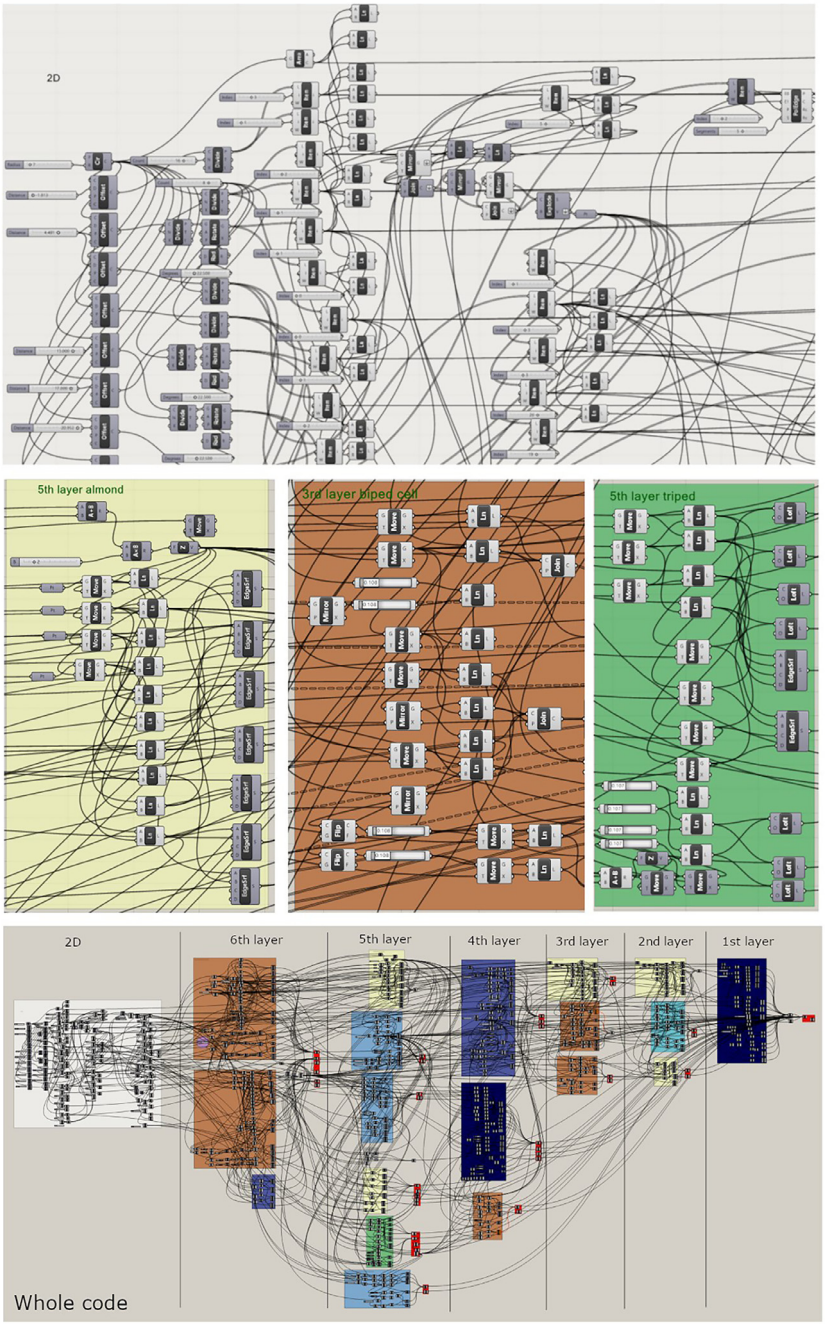

Fig. 7. Parts of the code.

tions in 2D plan, were not drawn in Takahashi's [3] plan (Fig. 9). That's why, in Takahashi's [3] plan, eight pointed star of second layer and the octagon of third layer have common contact points. But, they are actually separated because of in-between biped cells. Also, framing bipeds at the edges and bipeds at the fourth layer are not present in Takahashi's [3] plan. Moreover, the proportions of the almonds in the third layer are very different than the one that have been found in this study. Furthermore, Takahashi's [3] plan have five-pointed regular stars. Takahashi [3] might have drawn the plan from observation or a single photo reference and the result is clearly a more simplified and regular drawing.

In order to determine the similarities of the muqarnas plan of the Cenabi Ahmet Pasha Mosque main gate with the other muqarnas plans, the muqarnas drawings in the Uluengin's [4] book and the muqarnas plan drawings on Takahashi's [3] website were examined. A drawing that exactly coincides with the drawing of the main gate muqarnas of the Cenabi Ahmet Pasha Mosque has not been found. However, Takahashi's [3] Araboğlu Mosque (Karaman, Turkey) mihrab muqarnas plan drawing is similar to the Cenabi Ahmet Pasha Mosque main gate muqarnas plan (Fig. 9). In the plan of Araboğlu Mosque mihrab muqarnas, it is seen that there are five-armed stars in the lower right and left corners, the first layer begins with an eight-armed star (half four-armed star when the frame borders are determined), and the rows in the arrangement of cells in two dimensions are almost the same (almond cells, double deltoid cells, triped cells).

It has been discussed in the previous works of the author that the layouts used in the muqarnas plans may cause the arms of the stars in the muqarnas plan to be unequal [16,29]. The results of this study also show that the reference grid used in the muqarnas

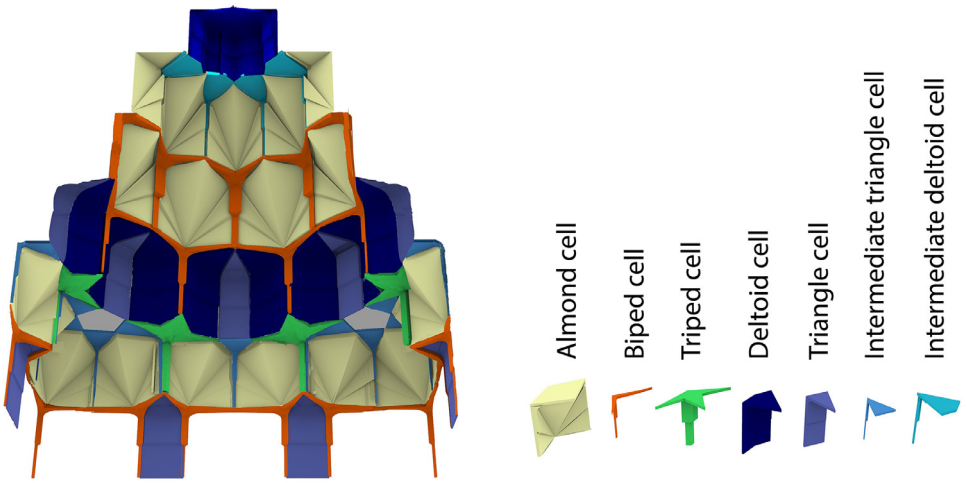

Fig. 8. 3D cell types of the Cenabi Ahmet Pasha Mosque main gate muqarnas.

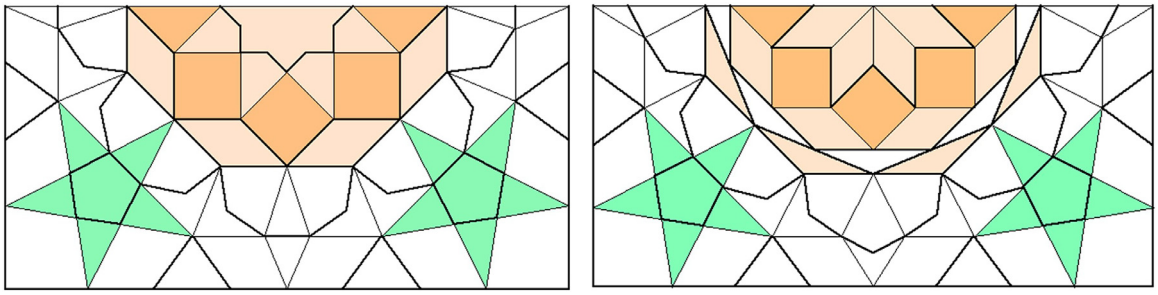

Fig. 9. Takahashi's (2023) drawing of Cenabi Ahmet Pasha Mosque main gate muqarnas plan (left side) and drawing of Araboğlu Mosque mihrab muqarnas plan (right side).

plan drawing may cause this situation. The muqarnas plan examined within the scope of this study fits on a rectangular frame. In this muqarnas plan, location of the five-armed stars in the lower right and left corners of the rectangular frame may have caused the star's arm lengths to be unequal.

It was observed that the radial layouts seen in the Mihrimah Sultan Mosque main gate muqarnas and Sehzade Mosque main gate muqarnas plans, which were examined according to the shape grammar theory in the previous study of Agirbas et al. [29], are similar to the radial layout in the Cenabi Ahmet Pasha Mosque main gate muqarnas plan. Although radial grid layouts are common in muqarnas plans, other grid types such as square grids (e.g. Suleymaniye Mosque main gate muqarnas plan) also exist. It was also observed that the cell types seen in the third dimension in the Atik Valide Mosque main gate muqarnas [16] are also seen in the Cenabi Ahmet Pasha Mosque main gate muqarnas plan.

5. Conclusion

In the direction of the obtained data, the muqarnas plan was examined in two dimensions according to the shape grammar theory and the possible layout scheme was emphasized. In line with the data obtained, cell types and the gathering of the cells in the third dimension were revealed. Additionally, an algorithmic model of the main gate muqarnas of Cenabi Ahmet Pasha Mosque was proposed. In the algoritmic model, each typical cell of the muqarnas was modelled parametrically, so that the size and shape can be differentiated as desired.

It can be said that the muqarnas plan of the Cenabi Ahmet Pasha Mosque main gate does not have a very complex schema and echoes the modest architectural style of the mosque. Although it does not precisely resemble the other muqarnas plan drawings in the literature, it is similar to other muqarnas in terms of plan scheme, cell arrangement and cell types.

This study's contributions can be summarized as below:

- The plan of the main gate muqarnas of Cenabi Ahmet Pasha Mosque was revealed by using photogrammetry method.
- The radial layout of the plan of the main gate muqarnas of Cenabi Ahmet Pasha Mosque was obtained with the help of shape grammar theory.
- The 3D cell unit information of the main gate muqarnas of Cenabi Ahmet Pasha Mosque was revealed.
- The comparison was made between the main gate muqarnas of Cenabi Ahmet Pasha Mosque and other muqarnas plans found in the literature.
- An algorithmic model based on parametric modelling of the individual cells in muqarnas for the creation of muqarnas of Cenabi Ahmet Pasha Mosque was proposed.
- A flowchart for the creation of an automated algorithmic model was proposed.

Availability of data and materials

Data available at https://doi.org/10.6084/m9.figshare.26809324

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